

14 PRTS

10/511451

DT05 Rec'd PCT/PTO 14 OCT 2004

- 1 -

DESCRIPTION

SYSTEM FOR ESTIMATING ATTITUDE OF  
LEG TYPE MOVING ROBOT ITSELF

5 Technical Field

The present invention relates to a system for estimating an attitude of a leg type moving robot itself.

Background Art

10 In general, a leg type moving robot, such as a bipedal moving robot, has a clinometer mounted on its body, and the posture of the robot is controlled so that an output of the clinometer (an inclination angle of the body relative to a vertical direction) is converged to an  
15 inclination angle of the body of a desired gait.

The clinometer is comprised of a gyro sensor for detecting an angular velocity of the body and an accelerometer (or a vertical indicator, such as a pendulum) for detecting a vertical direction (that is, the  
20 gravitational direction). The clinometer is basically adapted to estimate the inclination angle of the body by integrating angular velocities detected by the gyro sensor; however, simply integrating them accumulates errors (or a so-called "drift" is generated). For this  
25 reason, detected values of the accelerometer have been used to correct an estimated inclination angle obtained by integration. To be more specific, a difference between an

inclination angle relative to the direction of  
acceleration detected by the accelerometer and an  
inclination angle obtained by subjecting a detected value  
of the gyro sensor to an integrator is determined, and  
5 then a correction amount based on the difference (a sum of  
a value obtained by multiplying the difference by a  
predetermined gain and a value obtained by integrating the  
difference and multiplying it by a predetermined gain) is  
additionally supplied to the integrator so as to correct  
10 the inclination angle.

According to this method, however, there has been a  
possibility of opposite effect in that an error of an  
estimated inclination angle is increased by the aforesaid  
correction when the body of the robot is severely  
15 accelerated or decelerated during travel or the like,  
because acceleration from a motion of the body is added to  
an acceleration detected by the accelerometer in addition  
to a gravitational acceleration, preventing accurate  
detection of a direction of the gravitational acceleration.

20 Hereinafter, an inclination and a direction of a  
certain representative part, such as a body, will be  
referred to as "posture" as a generic term. The  
"inclination" refers to an angle formed relative to a  
vertical direction. The "direction" refers to a direction  
25 of a vector obtained by projecting the vector that  
indicates the front direction of a representative part  
onto a horizontal surface.

Generally, a representative part refers to a part provided with a clinometer composed of a gyro sensor and an accelerometer. Other parts may be specified as representative parts if joint displacement detectors, such as encoders, or displacement control actuators are provided on individual joints between the parts and a part with the clinometer, so that the inclinations of the parts can be calculated. For example, even if a head connected by a neck with a joint is provided with a gyro sensor and/or an accelerometer, a body may be defined as a representative part. In an embodiment to be discussed hereinafter, a body will be specified as a representative part.

Furthermore, a set of displacements of all joints is generally referred to as a posture. However, this will not mean a "posture" in the present embodiment unless otherwise specified.

In a conventional leg type moving robot, there has been a problem in addition to the aforesaid problem. Reaction forces generated when the robot swings its legs while it is moving cause rotational slippages (spins) to take place between its feet and a floor because of frictional forces between the feet (distal parts of the legs) and the floor exceeds its limit. As a result, the posture of the entire robot rotates about a vertical axis, deviating from the direction of a desired gait.

Complementarily, the body is not necessarily

maintained vertically (upright) at all times to generate only the desired gait for straight walking. Even in the desired gait, the entire robot or the body swings or inclines longitudinally or laterally. In other words, the rotation of the entire posture (or the rotation of the posture of a representative part, such as the body) exists also in the desired gait. In the present description, therefore, the rotation of a posture in a desired gait will be referred to as a desired posture rotation. A phenomenon to be mainly discussed in the present description is a rotation error of an actual posture of the entire robot (or a rotation of a posture of a representative part, such as a body) from the above desired posture rotation. Strictly speaking, the phenomenon should be referred to as "perturbation from a desired posture rotation" or "posture rotation perturbation". This, however, will be abbreviated to "posture rotation" hereinafter unless there is a possibility of confusion with a desired posture rotation.

Hereinafter, a phenomenon in which the entire robot posture-rotates about a vertical axis and deviates from a desired gait direction will be referred to, in particular, as a spin.

The present invention has been made with a view based on the background explained above, and it is an object thereof to provide a system for estimating a posture that enables a leg type moving robot to accurately estimate its

own posture. In particular, it is an object of the present invention to provide a system for estimating a posture that enables a leg type moving robot to accurately estimate its own posture even in a state wherein an acceleration is considerably changing in a horizontal direction or a vertical direction or in a state wherein the entire robot is undergoing a posture rotation (or a spin) due to a rotational slippage or the like between a foot sole of the robot and a floor.

#### Disclosure of Invention

To fulfill the aforesaid object, according to a first invention, there is provided a system for estimating a posture of a leg type moving robot controlled to follow a determined desired gait, comprising a posture angular velocity detecting means for detecting or estimating an actual posture angular velocity of a predetermined part of the robot, an accelerometer mounted on the robot, a motional acceleration estimating means for determining an estimated motional acceleration as an estimated value of an acceleration of the accelerometer itself that is generated by a motion of the robot by using a motional state amount of the robot that includes at least one of a desired motion of the desired gait, a detected displacement value of a joint of the robot, and a desired displacement value of the joint, and a posture estimating means for estimating an actual posture of the

predetermined part on the basis of at least a detected acceleration value by the accelerometer, the estimated motional acceleration, and the detected or estimated actual posture angular velocity.

5       According to the first invention, an estimated motional acceleration as an estimated value of an acceleration of the accelerometer itself that is generated by a motion of the robot is determined, using a motional state amount of the robot that includes at least one of a  
10   desired motion of the desired gait, a detected displacement value of a joint of the robot, and a desired displacement value of the joint. More specifically, a motional trajectory of the position of the accelerometer can be geometrically determined using the motional state  
15   amount, so that a motional acceleration of the accelerometer itself can be estimated from the motional trajectory. Then, an actual posture of the predetermined part is estimated on the basis of the estimated motional acceleration, a detected acceleration value by the  
20   accelerometer (a resultant value of a gravitational acceleration and a motional acceleration), and an actual posture angular velocity detected or estimated by the posture angular velocity detecting means. This makes it possible to estimate an actual posture of the  
25   predetermined part by correcting the detected or estimated actual posture angular velocity or an integrated value thereof while making up for influences of a motional

acceleration included in the detected acceleration value by the estimated motional acceleration. As a result, the actual posture of the predetermined part, which indicates the posture of the robot itself, can be accurately  
5 estimated.

According to a second invention, there is provided a system for estimating a posture of a leg type moving robot controlled to follow a determined desired gait, comprising an accelerometer mounted on the robot, a posture angular  
10 velocity detecting means for detecting or estimating an actual posture angular velocity of a predetermined part of the robot, a posture estimating means for determining an estimated posture angle value as an estimated value of an actual posture of the predetermined part on the basis of  
15 at least the detected or estimated actual posture angular velocity, a posture rotational error calculating means for determining a temporal variation of a posture rotational error as a posture rotational error variation, the posture rotational error variation indicating a difference between  
20 the estimated posture angle value and a desired posture angle of the predetermined part in the desired gait, a rotational center determining means for determining a rotational center of a change in the posture rotational error, and a motional acceleration estimating means for  
25 determining an estimated motional acceleration as an estimated value of an acceleration of the accelerometer itself generated by a motion of the robot, assuming that

the robot rotates about the rotational center with the posture rotational error variation, wherein the posture estimating means determines the estimated posture angle value while correcting it on the basis of at least a  
5 detected acceleration value by the accelerometer and the estimated motional acceleration.

According to the second invention, when determining the estimated motional acceleration, it is assumed that a variation in a certain posture rotational error, which is  
10 a difference between the estimated posture angle value and a desired posture angle of the predetermined part in the desired gait, is equivalent to a rotation of the entire robot about a certain rotational center with the posture rotational error variation. As a matter of fact, a  
15 rotational slippage (spin) taking place between a foot (a distal portion of a leg) of the robot and a floor, for example, would appear in the form of a variation in the posture rotational error. Furthermore, according to the second invention, based on the aforesaid assumption, an  
20 estimated motional acceleration as an estimated value of an acceleration of the accelerometer itself generated by a motion of the robot is determined. Therefore, an estimated motional acceleration providing an estimated value of the motional acceleration of the accelerometer  
25 itself can be determined by quantitatively determining an actual motion of the accelerometer itself generated by the aforesaid rotational slippage or the like. As a result,



an accurate estimated motional acceleration can be determined.

At this time, to determine an estimated motional acceleration, a position of the accelerometer (a position  
5 of a part provided with the accelerometer) may be sequentially estimated on the basis of, for example, the aforesaid assumption, and an estimated motional acceleration may be determined on the basis of a motional trajectory of the position. Alternatively, for example, a  
10 position of a certain representative location of the robot that is different from the part provided with the accelerometer (a position of a certain part of the robot, a landing position where a leg comes in contact with a ground in a landing motion, etc.) is estimated on the  
15 basis of the aforesaid assumption, and then an estimated value of the position of the representative location and a desired gait of the robot or a detected displacement value of a joint or a desired displacement value of the joint may be used to determine a motional trajectory of the  
20 position of the accelerometer by geometric computation (kinematics computation) so as to determine the estimated motional acceleration from the motional trajectory.

Complementarily, if a landing position of the robot (a position where the robot comes in contact with a floor) or  
25 a position of one part of the robot can be estimated, then the motional trajectory of any position of the robot can be determined by the geometric computation described above.

According to the second invention, the estimated posture angle value is determined while being corrected on the basis of at least a detected acceleration value by the accelerometer and the estimated motional acceleration determined as described above. Thus, as in the case of the first invention, it is possible to correct the estimated posture angle value while making up for influences of a motional acceleration included in the detected acceleration value by the estimated motional acceleration. As a result, the accuracy of an estimated posture angle value, which is an estimated value of an actual posture of the predetermined part, can be improved. In other words, the actual posture of the predetermined part as the self posture of the robot can be estimated with high accuracy.

To be more specific, in the second invention, the motional acceleration estimating means includes a means for determining a second coordinate system formed by rotating a first coordinate system, which is a coordinate system describing the aforesaid desired gait, about the aforesaid rotational center by the posture rotational error variation. Preferably, the estimated motional acceleration is determined such that an acceleration of the accelerometer itself observed from the first coordinate system that is determined from at least one of a desired motion of the desired gait, a detected displacement value of a joint of the robot, and a desired

displacement value of the joint, and an acceleration of the accelerometer itself when the accelerometer moving at the estimated motional acceleration is observed from the second coordinate system are the same (a third invention).

5       According to the third invention, the estimated motional acceleration is determined such that an acceleration of the accelerometer itself observed from the first coordinate system, that is, an acceleration of the accelerometer itself determined from at least one of a  
10   desired motion, a detected displacement value of a joint of the robot, and a desired displacement value of the joint when it is assumed the robot is moving on the first coordinate system according to the desired motion of a desired gait or the detected displacement value of the  
15   joint or the desired displacement value of the joint without rotational slippage or the like, and an acceleration of the accelerometer itself when the accelerometer in motion at the estimated motional acceleration is observed from the second coordinate system  
20   formed by rotating the first coordinate system about the rotational center by the posture rotational error variation are the same (coordinate components of an acceleration of the accelerometer itself on each coordinate system are the same on both coordinate systems).  
25   As a result, changes in posture rotational error can be properly reflected to determine an estimated motional acceleration, which is to be an estimated value of an

acceleration of the accelerometer itself, allowing an accurate estimated motional acceleration to be obtained. Consequently, the estimated posture angle value can be properly corrected, so that the accuracy of the estimated posture angle value can be improved.

In the first through third invention, the posture estimating means is preferably comprised of an integrating means for determining an estimated posture angle value as an estimated value of an actual posture of the predetermined part by integrating an input that includes at least a detected value of the posture angular velocity, a posture angle error estimating means for estimating an error of the estimated posture angle value on the basis of a difference between a detected acceleration value by the accelerometer and the estimated motional acceleration, and an input correcting means for correcting an input of the integrating means so as to bring the estimated error close to zero (a fourth invention).

More specifically, the difference (vector) between the detected acceleration value by the accelerometer and the estimated motional acceleration corresponds to a gravitational acceleration. If, however, the estimated posture angle value has an error, then the vector of the difference is not oriented in a vertical direction on a global coordinate system determined from the estimated posture angle value (a global coordinate system determined on an assumption that the estimated posture angle value is

correct). Here, the global coordinate system is a coordinate system fixed with respect to a floor (ground) in an environment in which the robot moves. Hence, it is possible to estimate an error of an estimated posture angle value (past value) on the basis of the difference (vector). In the fourth invention, an input of the integrating means is corrected to bring the estimated error close to zero, thereby correcting an estimated posture angle value, which is an output of the integrating means. This arrangement makes it possible to improve the accuracy of estimated posture angle value. To correct an input of the integrating means as described above, a manipulated variable is determined from, for example, the aforesaid error according to an appropriate feedback control law, and the manipulated variable is additionally supplied to the integrating means.

In the first through fourth inventions described above, the predetermined part is preferably a body (a base body to which legs are extendedly installed) of the robot (a fifth invention). This is because it is important to accurately determine a posture angle of the body for a robot to stably move.

In the first through fourth invention, if the predetermined part is the body of the robot, then it is particularly preferable that the posture estimated value corrected by the posture estimating means is an estimated value of an inclination angle of the body relative to the

vertical direction (a sixth invention). This is because the inclination angle of the body relative to the vertical direction is especially important for a robot to stably move.

5

#### Brief Description of the Drawings

Fig. 1 is a schematic diagram showing an outline of a skeleton of an entire construction of a bipedal moving robot as a leg type moving robot in an embodiment of the present invention; Fig. 2 is a schematic diagram schematically showing a construction of a foot portion of each leg shown in Fig. 1; Fig. 3 and Fig. 4 are a sectional diagram viewed sideways and a bottom view, respectively, showing a detailed construction of the foot portion of each leg; Fig. 5 is a block diagram showing a construction of a control unit provided in the robot shown in Fig. 1; and Fig. 6 is a block diagram showing a functional construction of the control unit shown in Fig. 5. Fig. 7 is an explanatory diagram showing a running gait of the robot; Figs. 8 (a), (b), and (c) are graphs illustrating a floor reaction force vertical component of a desired gait, a desired ZMP, and a setting example of a gain for estimating a self position/posture, respectively; Fig. 9 is a flowchart showing a processing of an essential section of a control unit in a first embodiment; Fig. 10 is a flowchart showing a processing for estimating the self position/posture in the flowchart shown in Fig. 9;

and Fig. 11 and Fig. 12 are diagrams for explaining the processing for estimating the self position/posture in the flowchart of Fig. 9. Fig. 13 is a block diagram showing a processing of an essential section of the processing for  
5 estimating the self position/posture in the flowchart of Fig. 9; Figs. 14 (a) and (b) are diagrams for explaining the processing illustrated in Fig. 13, and Fig. 15 is a graph showing a setting example of a gain used for the processing illustrated in Fig. 13.

10

#### Best Mode for Carrying Out the Invention

The following will explain a system for estimating a position of a leg type moving robot itself according to an embodiment of the present invention with reference to the  
15 accompanying drawings. As the leg type moving robot, a bipedal moving robot will be taken as an example.

Fig. 1 is a schematic diagram showing a general view of a bipedal moving robot as the leg type moving robot according to the present embodiment.

20

As shown in the diagram, a bipedal moving robot (hereinafter referred to as "the robot") 1 is equipped with a pair of right and left legs (leg links) 2, 2 provided such that they extend downward from a body (a base body of the robot 1) 3. Both legs 2, 2 share the  
25 same construction, each having six joints. The six joints of each leg are comprised of, in the following order from the body 3 side, joints 10R, 10L (symbols R and L mean

correspondence to the right leg and the left leg,  
respectively; the same will be applied hereinafter) for  
swinging (rotating) a hip (waist) (for rotating in a yaw  
direction relative to the body 3), joints 12R, 12L for  
5 rotating the hip (waist) in a roll direction (about an X  
axis), joints 14R, 14L for rotating the hip (waist) in a  
pitch direction (about a Y axis), joints 16R, 16L for  
rotating knees in the pitch direction, joints 18R, 18L for  
rotating ankles in the pitch direction, and joints 20R,  
10 20L for rotating the ankles in the roll direction.

A foot (foot portion) 22R(L) constituting a distal  
portion of each leg 2 is attached to the bottoms of the  
two joints 18R(L) and 20R(L) of the ankle of each leg 2.  
The body 3 is installed at the uppermost top of the two  
15 legs 2, 2 through the intermediary of the three joints  
10R(L), 12R(L) and 14R(L) of the hip of each leg 2. A  
control unit 60 or the like, which will be discussed in  
detail hereinafter, is housed inside the body 3. For  
convenience of illustration, the control unit 60 is shown  
20 outside the body 3 in Fig. 1.

In each leg 2 having the aforesaid construction, a  
hip joint (or a waist joint) is formed of the joint 10R(L),  
12R(L) and 14R(L), the knee joint is formed of the joint  
16R(L), and the ankle joint is formed of the joints 18R(L)  
25 and 20R(L). The hip joint and the knee joint are  
connected by a thigh link 24R(L), and the knee joint and  
the ankle joint are connected by a crus link 26R(L).



A pair of right and left arms 5, 5 are attached to both sides of upper portions of the body 3, and a head 4 is disposed at a top end of the body 3. These arms 5, 5 and the head 4 are not directly connected to a topic of the present invention, so that detailed explanation thereof will be omitted.

According to the construction described above, the foot 22R(L) of each leg 2 is given six degrees of freedom relative to the body 3. During a travel, such as walking, of the robot 1, desired motions of the two feet 22R and 22L can be accomplished by driving  $6 \times 2 = 12$  joints of the two legs 2, 2 together ("\*" in the present description will denote multiplication as scalar computation, while it will denote an outer product in vector computation) at appropriate angles. This arrangement enables the robot 1 to arbitrarily move in a three-dimensional space.

As shown in Fig. 1, a publicly known six-axis force sensor 50 is provided between the ankle joints 18R(L), 20R(L) and the foot 22R(L) of each leg 2. The six-axis force sensor 50 detects primarily whether the foot 22R(L) of each leg 2 is in contact with a ground, and a floor reaction force (landing load) acting on each leg 2, and it outputs detection signals of three-direction components  $F_x$ ,  $F_y$ , and  $F_z$  of a translational force of the floor reaction and three-direction components  $M_x$ ,  $M_y$ , and  $M_z$  of a moment to the control unit 60. Furthermore, the body 3 is equipped with an inclination sensor 54 for mainly

detecting an inclination (posture angle) of the body 3 relative to a Z-axis (vertical direction (gravitational direction)) and an angular velocity thereof, and detection signals thereof are supplied from the inclination sensor 54 to the control unit 60. The inclination sensor 54 is provided with a three-axis direction accelerometer and a three-axis direction gyro sensor, which are not shown, and detection signals of these sensors are used to detect an inclination and an angular velocity of the body 3 and also used to estimate a self position/posture of the robot 1. Although detailed structures are not shown, each joint of the robot 1 is provided with an electric motor 64 (refer to Fig. 5) for driving the joint, and an encoder (rotary encoder) 65 (refer to Fig. 5) for detecting a rotational amount of the electric motor 64 (a rotational angle of each joint). Detection signals of the encoder 65 are output from the encoder 65 to the control unit 60.

Furthermore, although not shown in Fig. 1, a joystick (operating device) 73 (refer to Fig. 5) is provided at an appropriate position of the robot 1. The joystick 73 is constructed in such a manner that a request regarding a gait of the robot 1, such as a request for turning the robot 1 that is moving straight, is input to the control unit 60 as necessary by operating the joystick 73.

Fig. 2 is a diagram schematically showing a basic construction of a distal portion (including each foot 22R(L)) of each leg 2 in the present embodiment. As shown

in the diagram, a spring mechanism 70 is installed between each foot 22R(L) and the six-axis force sensor 50, and a foot sole elastic member 71 made of rubber or the like is bonded to a foot sole (the bottom surface of each of the feet 22R and L). These spring mechanism 70 and the foot sole elastic member 71 constitute a compliance mechanism 72. The spring mechanism 70, which will be discussed in detail later, is constructed of a square guide member (omitted in Fig. 2), which is installed on the upper surface of the foot 22R(L), and a piston-shaped member (omitted in Fig. 2) installed adjacently to the ankle joint 18R(L) (the ankle joint 20R(L) being omitted in Fig. 2) and the six-axis force sensor 50, and housed in the guide member through the intermediary of an elastic member (rubber or spring) so that it may be jogged.

The foot 22R(L) indicated by a solid line shown in Fig. 2 is in a state where it is subjected to no floor reaction force. When each leg 2 is subjected to a floor reaction force, the spring mechanism 70 and the sole elastic member 71 of the compliance mechanism 72 flex, causing the foot 22R(L) to shift to the position/posture illustrated by a dashed line in the drawing. The structure of the compliance mechanism 72 is important not only to ease a landing impact but also to enhance controllability, as explained in detail in, for example, Japanese Unexamined Patent Publication Application 5-305584 proposed in the past by the present applicant.

More detailed construction of the foot 22R(L) including the compliance mechanism 72 (hereinafter referred to as the foot mechanism 22R(L) in some cases) will be further explained with reference to Fig. 3 and Fig. 4. Fig. 3 is a sectional view of the foot mechanism 22R(L) observed sideways, and Fig. 4 is a top plan view of the foot mechanism 22R(L) observed from its bottom surface.

The foot mechanism 22R(L) is equipped with a roughly plate-shaped foot plate member 102 as a skeletal member. A front end portion (tiptoe portion) and a rear end portion (heel portion) of the foot plate member 102 are slightly curved upward, the remaining portion being shaped like a flat plate. A guide member 103 having a square cross-sectional shape is fixedly provided on an upper surface of the foot plate member 102 such that an axial center thereof is vertically oriented. Inside the guide member 103, a movable plate (piston-shaped member) 104 is provided along an inner peripheral surface of the guide member 103 such that it is virtually movable in a vertical direction, the movable plate 104 being connected to the ankle joints 18R(L) and 20R(L) through the intermediary of the six-axis force sensor 50.

A rim of the bottom surface of the movable plate 104 is connected to the upper surface of the foot plate member 102 through the intermediary of a plurality of elastic members 106 made of an elastic material, such as rubber (shown as a spring in the drawing). Hence, the foot plate

member 102 is connected to the ankle joint 18R(L) through the intermediary of the elastic member 106, the movable plate 104, and the six-axis force sensor 50. The interior of the guide member 103 (the space under the movable plate 104) is opened to the air through the intermediary of a hole or gap, which is not shown. Atmospheric air freely goes into and out of the guide member 103. The guide member 103, the movable plate 104, and the elastic member 106 constitute the spring mechanism 70 shown in Fig. 2.

A ground contact member 71 serving as the sole elastic member 71 shown in Fig. 2 mentioned above is attached to a bottom surface (lower surface) of the foot plate member 102. The ground contact member 71 is an elastic member (elastic member directly coming in contact with a floor surface) provided between the foot plate member 102 and the floor surface with the foot mechanism 22R(L) grounded. In the present embodiment, the ground contact member 71 is secured to four corners of the ground contact surface of the foot plate member 102 (both side portions of the tiptoe of the foot plate member 102 and both side portions of the heel).

The ground contact member 71 is formed of two layers, namely, a soft layer 107a made of a relatively soft rubber material and a hard layer 107b made of a relatively hard rubber material, which are vertically stacked. The hard layer 107b is provided on the lowermost surface side as the ground contact surface coming directly in contact with

a floor surface when the leg 2 lands.

The foot mechanism 22R(L) is provided with a landing shock absorber 108 in addition to the above components. The landing shock absorber 108 has a bag-shaped member 109  
5 attached to the bottom surface of the foot plate member 102, and a passage 110 for entry and exit of air (atmospheric air) serving as a compressive fluid in relation to the interior of the bag-shaped member 109.

The bag-shaped member 109 surrounded by the ground  
10 contact member 71 is provided nearly in a central area of the bottom surface of the foot plate member 102. The bag-shaped member 109 is made of an elastic material, such as rubber, so as to be deformable. The bag-shaped member 109 is shaped like a cylindrical container that is open upward,  
15 as indicated by a solid line in Fig. 3, in its natural state wherein it has developed no resilient deformation caused by an external force. The entire peripheral edge of the opening of the bag-shaped member 109 is secured to the bottom surface of the foot plate member 102, and  
20 covered by the foot plate member 102. The bag-shaped member 109 is provided such that the bottom portion of the bag-shaped member 109 juts out downward beyond the ground contact member 71 in its natural state wherein it is shaped like the cylindrical container. In other words,  
25 the bag-shaped member 109 has a height (a distance from the bottom surface of the foot plate member 102 to the bottom portion of the bag-shaped member 109) that is

larger than the thickness of the ground contact member 71. Hence, in a state wherein the foot plate member 102 is grounded through the intermediary of the ground contact member 71 (the leg 2 being landed), the bag-shaped member 109 is compressed in the direction of the height of the bag-shaped member 109 due to a floor reaction force, as indicated by a virtual line in Fig. 3.

In the present embodiment, the natural state wherein the bag-shaped member 109 is shaped like the cylindrical container is a state in which the bag-shaped member 109 is inflated. Since the bag-shaped member 109 is formed of an elastic material, it has a force for restoring its original shape (the cylindrical container shape) when compressed.

The passage 110 provides an inflow/outflow means for air to go into/out of the bag-shaped member 109. In the present embodiment, the passage 110 is formed of a channel hole drilled in the foot plate member 102 to provide communication between the interior of the bag-shaped member 109 and the interior of the guide member 103. In this case, as previously described, the interior of the guide member 103 is opened to the atmosphere, meaning that the passage 110 provides communication for the interior of the bag-shaped member 109 to the atmosphere. Thus, air in the atmosphere is free to go into/out of the bag-shaped member 109 through the intermediary of the passage 110. The bag-shaped member 109 is filled with air when the bag-

shaped member 109 is in its inflated state (natural state),  
the pressure therein being equivalent to atmospheric  
pressure. The passage 110 is a choke passage so that a  
fluid resistance is generated when air moves into or out  
5 of the bag-shaped member 109.

Fig. 5 is a block diagram showing a construction of  
the control unit 60. The control unit 60 is comprised of  
a microcomputer, and includes a first calculation unit 90  
and a second calculation unit 92 constructed of CPUs, an  
10 A/D converter 80, a counter 86, a D/A converter 96, a RAM  
84, a ROM 94, and a bus line 82 for transferring data  
among them. In the control unit 60, output signals of the  
six-axis force sensor 50, the inclination sensor 54 (an  
accelerometer and a rate gyro sensor), the joystick 73,  
15 etc. of each leg 2 are converted into digital values by  
the A/D converter 80 and sent to the RAM 84 via the bus  
line 82. Outputs of the encoder 65 (rotary encoder) of  
each joint of the robot 1 are supplied to the RAM 84 via  
the counter 86.

20 As will be discussed hereinafter, the first  
calculation unit 90 generates desired gaits, calculates a  
joint angle displacement command (a displacement angle of  
each joint or a command value of a rotational angle of  
each electric motor 64), and sends the calculation result  
25 to the RAM 84. The second calculation unit 92 reads an  
actual measurement value of a joint angle detected on the  
basis of an output signal of the encoder 65 and the joint



angle displacement command from the RAM 84 to calculate a manipulated variable required for driving each joint, and outputs the calculated variable to the electric motor 64 for driving each joint through the intermediary of the D/A converter 96 and a servo amplifier 64a.

Fig 6 is a block diagram showing the entire functional construction of a control unit of the leg type moving robot in accordance with the present embodiment. A portion except for the "actual robot" in Fig. 6 is constituted by processing functions implemented by the control unit 60 (primarily the functions of the first calculation unit 90 and the second calculation unit 92). In the following explanation, the symbols R and L will be omitted unless it is necessary to discriminate right and left of the legs 2.

The control unit 60 is equipped with a gait generator 200 for generating and outputting desired gaits of the robot 1 freely in real time, a self position/posture estimator 214, etc. The self position/posture estimator 214, details of which will be discussed later, is adapted to carry out processing related to a characteristic portion of the present invention and estimate a position and a posture (a position and a posture in a global coordinate system) of the robot 1.

A desired gait output by the gait generator 200 is constituted of a desired body position/posture trajectory (trajectory of a desired position and a desired posture of

the body 3), a desired foot position/posture trajectory  
(trajectory of a desired position and a desired posture of  
each foot 22), a desired arm posture trajectory  
(trajectory of a desired posture of each arm 5), a desired  
5 total floor reaction force central point (desired ZMP)  
trajectory, and a desired total floor reaction force  
trajectory. If a movable part in addition to the legs 2  
and the arms 5 is provided on the body 3, then a desired  
position/posture trajectory of the movable part is added  
10 to the desired gait.

Complementary explanation will be added to meanings  
or definitions of terms used in the embodiment of the  
present invention. The term "trajectory" in the above  
gait means a temporal change pattern (time series pattern),  
15 and may be referred to as "pattern" in place of  
"trajectory" in the following explanation. Furthermore, a  
"posture" of each part collectively means an inclination  
and direction of the part. The term "inclination" means  
an angle of the part relative to a vertical direction, and  
20 the term "direction" is the direction of a vector when the  
vector indicating a front direction of the part is  
projected onto a horizontal surface. For example, the  
inclination in a posture of a body is comprised of an  
inclination angle (posture angle) of the body 3 in the  
25 roll direction (about the X-axis) relative to the Z-axis  
(vertical axis) and an inclination angle (posture angle)  
of the body 3 in the pitch direction (about the Y-axis)

relative to the Z-axis. The direction of the body 3 is represented by means of a rotational angle in the yaw direction (about the Z-axis) of the vector when the vector indicating a front direction of the body 3 is projected onto a horizontal surface. A foot posture is represented by means of a spatial azimuth of two axes fixedly set on each foot 22. Regarding a landing posture, in particular, of the foot 22, the landing posture basically indicates the direction of the landed foot 22. Specifically, the landing posture represents the direction of a vector when the vector directing from the heel of the landed foot 22 toward its tiptoe is projected onto a horizontal surface. A desired arm posture is represented by relative postures of all parts of the arm 5 with respect to the body 3.

A body position means a predetermined position of the body 3, specifically, the position of a preset representative point of the body 3. Similarly, a foot position means the position of a preset representative point of each of the foot 22R and 22L. A body velocity means a moving velocity of the aforementioned representative point of the body 3, and a foot velocity means a moving velocity of the aforementioned representative point of each of the foot 22R and 22L.

The term "desired" in a desired gait, such as in a desired body position/posture, will be frequently omitted in the following explanation when there is no danger of misunderstanding. Of gaits, constituent elements other

than those related to a floor reaction force, that is, the gaits related to motions of the robot 1, such as a foot position/posture and a body position/posture, will be collectively referred to as "motion."

5           A floor reaction force (floor reaction force comprised of a translational force and moment) of each of the feet 22R, L is referred to as "reaction force of each foot," and a resultant force of the floor reaction forces of all (two) feet 22R and 22L of the robot 1 will be  
10 referred to as "total floor reaction force." In the following explanation, however, each foot floor reaction force will hardly be referred to, so that "floor reaction force" will be handled as having the same meaning as "total floor reaction force" unless otherwise specified.

15           A desired floor reaction force is generally expressed by a point of action and a force (translational force) applied to the point of action and moment of the force. The point of action may be set at any location, so that innumerable expressions are possible for the same desired  
20 floor reaction force. If, however, a desired floor reaction force is expressed using especially the aforesaid desired floor reaction force central point as the point of action, then the moment of the force will be zero except for a component of a vertical axis.

25           In the case of a gait that satisfies dynamic equilibrium conditions, a ZMP calculated from a desired motion trajectory (a point at which moment of a resultant

force of an inertial force and gravity of the robot 1  
calculated from the desired motion trajectory acts about  
the point becomes zero except for a vertical-axis  
component) agrees with a central point of a desired total  
5 floor reaction force. Therefore, providing a desired ZMP  
trajectory can be regarded as equivalent to providing a  
desired total floor reaction force central point  
trajectory (refer to, for example, PCT publication of  
unexamined application WO/02/40224 by the present  
10 applicant for details).

From the background described above, in the  
description of PCT publication of unexamined application  
WO/02/40224, a desired gait has been defined as follows:  
a) In a broad sense, a desired gait is a set of a desired  
15 motion trajectory of a period of one step or a plurality  
of steps and a desired floor reaction force trajectory.  
b) In a narrow sense, a desired gait is a set of a desired  
motion trajectory of a period of one step and its ZMP  
trajectory.  
20 c) A series of gaits is formed of several gaits that are  
connected.

To walk the robot 1, a vertical position of the body  
(a height of the body) is determined by a body height  
determining technique proposed previously in Japanese  
25 Unexamined Patent Application Publication No. 10-86080 by  
the present applicant. This subordinately determines a  
translational force component of a floor reaction force,

so that ZMP alone has been adequate as a physical amount to be explicitly set for the floor reaction force of a desired gait. Accordingly, in the description of PCT publication of unexamined application WO/02/40224, the  
5 above b) has been adequate as the desired gait in the narrow sense. To run the robot 1, a floor reaction force vertical component is also important for control, so that it is preferable to explicitly set the floor reaction force vertical component. For this reason, the following  
10 b') has been adopted for a desired gait in a narrow sense in PCT application (PCT/JP02/13596) previously proposed by the present applicant.

b') A desired gait in a narrow sense is a set of a desired motion trajectory of a period of one step and its ZMP  
15 trajectory, and a track of a floor reaction force vertical component.

In the present description, the term "desired gaits" used hereinafter will mean the desired gaits in a narrow sense unless otherwise specified. Furthermore, the term  
20 "one step" of a desired gait will mean a period from the moment one leg 2 of the robot 1 touches the ground to the moment the other leg 2 touches the ground.

Needless to say, a two-leg supporting period will refer to a period during which the robot 1 supports its  
25 own weight by the two legs 2, 2, a one-leg supporting period will refer to a period during which the robot 1 supports its own weight only by one leg 2, and a floating

period will refer to a period during which the two legs 2, 2 are apart from a floor (in the air).

In the one-leg supporting period, the leg 2 not supporting the self-weight of the robot 1 will be referred to as a "free leg," and the leg 2 supporting the self-weight will be referred to as a "supporting leg." While the robot 1 is walking, the two-leg supporting period and the one-leg supporting period are alternately repeated. While the robot 1 is running, the one-leg supporting period and the floating period are alternately repeated. In this case, during the floating period of running, both legs 2, 2 do not support the self-weight of the robot 1; however, the leg 2 that was a free leg and the leg 2 that was a supporting leg during a one-leg supporting period immediately before the floating period will be referred to as a "free leg" and a "supporting leg," respectively, even in the floating period.

Positions/postures of individual parts of the robot 1 in desired gaits, including a desired body posture, a desired body position, a desired foot position/posture, and a desired arm posture, will be described by means of a supporting leg coordinate system. The supporting leg coordinate system is a coordinate system fixed to a floor surface having its origin near a ground contact surface of the foot 22 of a supporting leg. More detailedly, as described in Patent No. 3273443 by the present applicant, in the coordinate system, the origin is a point of the

center of an ankle joint of the supporting leg vertically projected toward the ground contact surface when the foot 22 of the supporting leg is rotated to a horizontal posture without allowing the foot 22 to slip against the ground contact surface. A horizontal axis (an axis in the longitudinal direction of the foot 22) extending toward a tiptoe of the supporting leg foot 22 provides the X-axis, a vertical axis provides the Z-axis, and a coordinate axis (axis in the lateral direction of the foot 22) orthogonal to these X-axis and Z-axis provides the Y-axis.

The gait generator 200 according to the embodiment of the present invention uses landing positions/postures of the foot 22 of a free leg and required values (desired values) of landing time up to two steps ahead as inputs to generate a desired gait composed of a desired body position/posture trajectory, a desired foot position/posture trajectory, a desired ZMP trajectory, a desired floor reaction force vertical component trajectory, and a desired arm posture trajectory. At this time, some of parameters defining these trajectories (referred to as gait parameters) are corrected to satisfy continuity of a gait.

To generate desired gaits, a dynamic model of the robot 1 is used. As the dynamic model, for example, a simplified model described in the aforesaid PCT publication of unexamined application WO/02/40224 or a multi-mass point model (full model) disclosed in Japanese



Unexamined Patent Application Publication No. 2002-326173  
proposed by the present applicant may be used.

The gait generator 200 defines a desired gait  
(desired gait in the narrow sense) for one step from the  
5 moment one leg 2 of the robot 1 touches the ground to the  
moment the other leg 2 grounds as a unit, and generates  
the desired gait for the one step in order. Here, a gait  
that is currently generating or will be generated will be  
referred to as a "current time gait," the next gait will  
10 be referred to as a "next time gait," and a gait after  
next will be referred to as a "next but one time gait."  
Furthermore, a desired gait generated one step before the  
current time gait will be referred to as a "last time  
gait."

15 Some of desired gaits generated by the gait generator  
200 will be illustratively outlined. For example, a  
desired foot position/posture trajectory is generated  
using a finite-duration setting filter disclosed in Patent  
No. 3233450 by the present applicant. In the processing  
20 for generating a foot position/posture trajectory by the  
finite-duration setting filter, a foot position trajectory,  
for example, is generated such that the foot 22 starts  
moving toward a desired landing position (a required value  
of the landing position) while gradually accelerating it,  
25 and then gradually decelerate its velocity to zero or  
substantially to zero by desired landing time (a required  
value of landing time) so as to stop when it reaches the

desired landing position at the desired landing time. The same applies to a foot posture trajectory. In the desired foot position/posture trajectory thus generated, a ground velocity at a landing moment is zero or substantially zero, so that a landing impact at landing from the aforesaid floating period can be reduced especially when running the robot 1.

When running the robot 1 in the same manner as a human runs, as shown in Fig. 7, a desired floor reaction force vertical component trajectory and a desired ZMP trajectory (specifically in the X-axis direction (the longitudinal direction of the supporting leg foot 22) of the supporting leg coordinate system), for example, are set by the patterns indicated by solid lines in Fig. 8(a) and Fig. 8(b), respectively. First through third diagrams of Fig. 7 schematically show motional states of the two legs 2, 2 of the robot 1 at a start point, a mid point, and an end point of the one-leg supporting period, and a fourth diagram and a fifth diagram schematically illustrate motional states of the two legs 2, 2 of the robot 1 at a mid point of the floating period and an end point of the floating period (the start point of the next one-leg supporting period).

When running the robot 1, a desired floor reaction force vertical component trajectory basically exhibits a pattern jutting upward in the one-leg supporting period, and maintains zero during the floating period. When

walking the robot 1, the desired floor reaction force vertical component trajectory is set, for example, as indicated by the two-dot chain line in Fig. 8(a). In this case, the upwardly protuberant portion of the two-dot  
5 chain line corresponds to the two-leg supporting period, while the downwardly protuberant portion corresponds to the one-leg supporting period. Regardless of whether the robot 1 is running or walking, the desired ZMP is basically set around the center in the ground contact  
10 surface (more specifically, in a so-called supporting polygon) of the leg 2 of the robot 1.

Fig. 9 is a flowchart (structural flowchart) showing gait generation processing of the gait generator 200 and a self position/posture estimation processing of the self  
15 position/posture estimator 214 shown in Fig. 6.

First, various initializing operations, such as initializing time  $t$  to zero, are performed in S010.

Next, the program proceeds to S014 via S012 and waits for a timer interrupt for each control cycle. The control  
20 cycle is denoted by  $\Delta t$ .

Then, the program proceeds to S016 to estimate self position/posture by the self position/posture estimator 214. The processing in S016 constitutes a characteristic of the self position/posture estimator of the leg type  
25 moving robot in accordance with the present application; the description thereof will be given hereinafter.

Subsequently, the program proceeds to S018 to

determine whether a gait is switching (whether it is the time to start generating a new current time gait after completion of generating a last time gait). If the determination result is YES, then the program proceeds to S020, or if it is NO, then the program proceeds to S032. Processing after S020, which will be described hereinafter, has been explained in detail in PCT publication of unexamined application WO/02/40224 or the aforesaid PCT application PCT/JP02/13596 previously proposed by the present applicant; therefore, only a brief explanation will be given in the present description.

When proceeding to S020, time t is initialized to zero. The program then proceeds to S022 to read a next time gait's supporting leg coordinate system (specifically the position and direction), the next but one time gait's supporting leg coordinate system (specifically the position and direction), and the current time gait's cycle and the next time gait's cycle.

The next time gait's supporting leg coordinate system and the next but one time gait's supporting leg coordinate system are determined according to the definitions of the aforesaid supporting leg coordinate systems on the basis of a required value of a landing position/posture (desired landing position/posture) of a free leg foot 22 of a first step (the free leg foot 22 of the current time gait) and a required value of a landing position/posture (desired landing position/posture) of a free leg foot 22 of a

second step (the free leg foot 22 of the next time gait) specified primarily by operating the joystick 73.

The current time gait's cycle and the next time gait's cycle are determined on the basis of a required value of landing time (desired landing time) of the free leg foot 22 of the first step and a required value of landing time (desired landing time) of the free leg foot 22 of the second step.

The aforesaid required values of landing position/posture and the required values of landing time of the free leg foot 22, or positions and directions in the supporting leg coordinate systems and gait cycles may be stored beforehand as walking schedules or determined on the basis of commands (requests) from a steering device, such as the joystick 73, and a walking history up to that moment.

Then, the program proceeds to S024 wherein gait parameters of a normal turning gait connected to the current time gait are determined on the basis of mainly the next time gait's supporting leg coordinate system, the next but one time gait's supporting leg coordinate system, the current time gait's cycle, and the next time gait's cycle determined in S022. Primarily, a foot trajectory parameter defining a desired foot position/posture trajectory, a reference body posture trajectory parameter defining a reference trajectory of a desired body posture, an arm posture trajectory parameter defining a desired arm

posture trajectory, a ZMP trajectory parameter defining a desired ZMP trajectory, and a floor reaction force vertical component trajectory parameter defining a desired floor reaction force vertical component trajectory are determined. To illustrate, for example, the floor reaction force vertical component trajectory parameter, time and value of a bend point of the pattern shown in Fig. 9(a) are determined as the floor reaction force vertical component trajectory parameter.

Here, the normal turning gait means a cyclic gait that is free of discontinuity in a motional state of the robot 1 at a boundary of the gait when the gait is repeated ("normal turning gait" may hereinafter be abbreviated to "normal gait").

A one-cycle gait of the normal turning gait is composed of a first turning gait and a second turning gait. The first turning gait corresponds to a gait in which the supporting leg foot 22 corresponding to the supporting leg coordinate system of the current time gait is moved to a position/posture corresponding to the next but one time gait's supporting leg coordinate system. The second turning gait corresponds to a gait in which the supporting leg foot 22 corresponding to the supporting leg coordinate system of the next time gait is moved to a position/posture corresponding to a next but two time gait's supporting leg coordinate system. In this case, the next but two time gait's supporting leg coordinate

system corresponds to a desired landing position/posture of the free leg foot 22 of the second turning gait.

Furthermore, the next but two time gait's supporting leg coordinate system is set such that the position/posture

5 (position and direction) of the next but two time gait's supporting leg coordinate system observed from the next but one time gait's supporting leg coordinate system (the supporting leg coordinate system of the second turning gait) agrees with the position/posture (position and

10 direction) of the next time gait's supporting leg coordinate system (landing position/posture of the free leg foot 22 of the current time gait) observed from the current time gait supporting leg coordinate system. The

15 term "turning" is used for normal turning gaits, because it means moving straight when a turning rate is set to zero, and moving straight can be included in turning in a broad sense.

Normal turning gaits are virtual cyclic gaits provisionally prepared to determine a divergent component  
20 at an end of the current time gait or a body vertical positional velocity by the gait generator 200, and are not directly output from the gait generator 200 to actually control the robot 1.

The term "divergent" means that the position of the  
25 body shifts away from the position of the two foot portions (feet). A value of a divergent component is a numeral value indicating how far the position of the body

of the bipedal moving robot shifts from the position of the two foot portions (feet) (strictly speaking, a numeral value indicating how far it shifts from the origin of a supporting leg coordinate system set on a supporting leg ground contact surface), and it is expressed by a position of the body 3 in the horizontal direction and a velocity function thereof.

In the present embodiment, a normal gait following the current time gait to be generated is set on the basis of a move request (a required value of a landing position/posture of the foot 22 of a free leg up to the next two steps and landing time or the like), and an initial divergent component of a normal gait is determined, and then the current time gait is generated so that a terminal divergent component of the current time gait agrees with the initial divergent component of the normal gait. The details of S024 have been explained in the aforesaid PCT publication of unexamined application WO/02/40224 or PCT/JP02/13596 proposed by the present applicant, so that any further explanation will be omitted.

After the processing shown by S010 through S024 is carried out, the program proceeds to S026 wherein an initial condition (an initial body horizontal positional velocity component, an initial body vertical positional velocity, an initial divergent component, an initial body posture angle, and an angular velocity) of the normal turning gait is determined. The details of S026 have been



explained in the aforesaid PCT publication of unexamined application WO/02/40224 or PCT/JP02/13596, so that any further explanation will be omitted.

Subsequently, the program proceeds to S028 wherein  
5 gait parameters for the current time gait are determined (some being provisionally determined). In this case, the gait parameters for the current time gait to be determined mainly include a foot trajectory parameter, a reference body posture trajectory parameter, an arm posture  
10 trajectory parameter, a desired ZMP trajectory parameter, and a desired floor reaction force vertical component trajectory parameter, as in the case of the gait parameters for a normal turning gait. The trajectories defined by the individual parameters are determined so  
15 that they continue to the trajectory of the normal turning gait. Among these parameters, however, the desired ZMP trajectory parameter is provisional. The details of the processing of S028 have been explained in the aforesaid PCT publication of unexamined application WO/02/40224 or  
20 PCT/JP02/13596, etc. so that any further explanation will be omitted.

Next, the program proceeds to S030 wherein a gait parameter of the current time gait is corrected so that a terminal divergent component of the current time gait  
25 agrees with an initial divergent component of a normal gait. The gait parameter corrected here is the desired ZMP trajectory parameter.

After the current time gait parameter are corrected in S030, or if a determination result of S018 is NO, then the program proceeds to S032 to determine a current time gait instantaneous value. The details of the processing have been explained in the aforesaid PCT publication of unexamined application WO/02/40224 or PCT/JP02/13596, etc. so that any further explanation will be omitted.

The program then proceeds to S034 wherein an arm swinging operation for canceling a spin force is determined, as in the case of the processing of S032 in an embodiment of PCT application No. PCT/JP02/13596.

The program then proceeds to S036 wherein it increases gait generating time  $t$  by  $\Delta t$ , and returns to S014 to continue generating gaits as described above.

The above describes the processing for generating desired gaits carried out in the gait generator 200, and the processing for estimating self positions/postures carried out in the self position/posture estimator 214.

Referring to Fig. 6, control processing by the control unit 60 according to the present embodiment will be further explained. In the gait generator 200, desired gaits are generated, as described above. Among generated desired gaits, a desired body position/posture (trajectory) and a desired arm posture trajectory are directly sent to a robot geometric model (inverse kinematics operation part) 202.

A desired foot position/posture (trajectory), a

desired ZMP trajectory (desired total floor reaction force  
central point trajectory), and a desired total floor  
reaction force (trajectory) (a desired floor reaction  
force horizontal component and a desired floor reaction  
5 force vertical component) are directly sent to a  
composite-compliance operation determiner 204 and also to  
a desired floor reaction force distributor 206. In the  
desired floor reaction force distributor 206, a desired  
total floor reaction force is distributed to the feet 22R  
10 and 22L, and a desired floor reaction force central point  
of each foot and a desired floor reaction force of each  
foot are determined. The determined desired floor  
reaction force central point of each foot and the desired  
floor reaction force of each foot are sent to the  
15 composite-compliance operation determiner 204.

The composite-compliance operation determiner 204  
generates a corrected desired foot position/posture  
trajectory with deformation compensation and sends it to  
the robot geometric model 202. Upon receipt of a desired  
20 body position/posture (trajectory) and a corrected desired  
foot position/posture (trajectory) with deformation  
compensation, the robot geometric model 202 calculates  
joint displacement commands (values) of twelve joints  
(10R(L), etc.) of the legs 2, 2 that satisfy them and  
25 sends the calculated commands to a displacement controller  
208. The displacement controller 208 performs follow-up  
control on the displacements of the twelve joints of the

robot 1, using the joint displacement commands (values) calculated by the robot geometric model 202 as desired values.

A floor reaction force generated in the robot 1 (more specifically, an actual floor reaction force of each foot) is detected by the six-axis force sensor 50. The detected value is sent to the composite-compliance operation determiner 204. As will be discussed later in relation to S016 of Fig. 9, inclination components, namely, actual body posture angle errors  $\theta_{errx}$  and  $\theta_{erry}$ , in a difference between an estimated body posture determined and a desired body posture generated by the gait generator 200 are supplied to a posture stabilization control operation part 212.  $\theta_{errx}$  denotes an inclination component in the roll direction (about the X-axis) and  $\theta_{erry}$  denotes an inclination component in the pitch direction (about the Y-axis). The posture stabilization control operation part 212 calculates a compensation total floor reaction force moment  $M_{dmd}$  about a desired total floor reaction force central point (desired ZMP) for restoring the inclination of the body posture of the robot 1 to the inclination of the body posture of a desired gait. The compensation total floor reaction force moment  $M_{dmd}$  is supplied to the composite-compliance operation determiner 204. The composite-compliance operation determiner 204 modifies a desired foot position/posture on the basis of an input value. More specifically, the composite-compliance

operation determiner 204 modifies the desired foot position/posture received from the gait generator 200 to determine the corrected desired foot position/posture (trajectory) with deformation compensation such that an  
5 actual total floor reaction force (a resultant force of all actual foot floor reaction forces, including both translational force and moment) agrees with a resultant force of the desired total floor reaction force, which is the resultant force of individual desired foot floor  
10 reaction forces, and the total compensation floor reaction force moment  $M_{dmd}$ . It is actually impossible, however, to make every state agree with a desired state, so that a trade-off relationship is established therebetween to make them compromisingly agree with each other. More  
15 specifically, control errors with respect to desired foot positions/postures and desired floor reaction forces are weighted, and control is carried out to minimize the weighting average of control errors (or squares of control errors).

20 Complementarily, a corrected desired foot position/posture (trajectory) with deformation compensation is a desired foot position/posture (trajectory) obtained by determining a deformation amount of a deformation mechanism (a columnar rubber, a sole  
25 sponge, and a bag-shaped air damper for absorbing shocks) of a foot required to generate a desired value of a floor reaction force corrected by the composite-compliance

operation determiner 204 by using a dynamic model (a spring damper model or the like) of the deformation mechanism, and then by making a correction so that the determined deformation amount is generated.

5       The following will explain in detail self position/posture estimation processing in S016 in the present embodiment with reference to Fig. 10 showing a flowchart thereof.

10       In S2200 of Fig. 10, detected values of the gyro sensor provided in the inclination sensor 54 of the body 3, that is, angular velocities (angular velocities in three-axis directions) of the body 3, are integrated by an integrator to determine an estimated body posture (hereinafter referred to as an inertial-navigation-like  
15       estimated body posture in some cases). The estimated body posture is described in a global coordinate system. In this processing, drift correction for correcting a drift from accumulation of integration errors of the detected values of the gyro sensor is also performed using mainly  
20       an estimated body position, which is an estimated value of a body position determined by the processing from S2202 to S2214 to be discussed hereinafter in a previous control cycle (a preceding or earlier control cycle). This will be discussed in more detail hereinafter.

25       Subsequently, the program proceeds to S2202 to calculate a difference between a variation in an estimated body posture observed from the global coordinate system

(an estimated body posture determined in S2200) between control cycles (between the preceding control cycle and the present control cycle) and a variation in a body posture of a desired gait observed from the global coordinate system between the control cycles, as a variation in posture rotational error. In other words, the difference between a changing velocity of an estimated body posture observed from the global coordinate system and a changing velocity of a desired body posture is calculated as a variation in the posture rotational error.

The body posture of a desired gait observed from the global coordinate system refers to the body posture observed from the global coordinate system when it is assumed that the robot 1 has moved according to the desired gait without the body 3 inclining its posture or spinning (shifting from a desired body posture) during a control cycle on the current estimated supporting leg coordinate system (more specifically, on an estimated supporting leg coordinate system determined in the preceding control cycle). However, the estimated supporting leg coordinate system refers to a supporting leg coordinate system corresponding to an estimated position/posture of the actual supporting leg foot 22 of the robot 1. This means that the estimated supporting leg coordinate system is defined by the aforesaid supporting leg coordinate system, more specifically, it is a coordinate system wherein its origin is a point of the

center of an ankle of the supporting leg vertically  
projected toward a ground contact surface when the foot 22  
of the supporting leg of the actual robot 1 is rotated  
from the estimated position/posture to a horizontal  
5 posture without allowing the foot 22 to slip against the  
ground contact surface, the horizontal axis toward a  
tiptoe of the supporting leg foot 22 being defined as the  
X-axis, the vertical axis being defined as the Z-axis, and  
a coordinate axis orthogonal to these axes being defined  
10 as the Y-axis.

The program then proceeds to S2204 to determine a  
posture rotational center. To be more specific, a desired  
ZMP at a particular moment (a current value of the desired  
ZMP) is determined as the posture rotational center. In a  
15 floating period while the robot 1 is running, the gravity  
of the robot 1 in, for example, a desired gait is  
determined as the posture rotational center.

The program then proceeds to S2206 to determine the  
position and posture obtained by rotating the current  
20 estimated supporting leg coordinate system (the estimated  
supporting leg coordinate system determined in the  
preceding control cycle, which is the estimated supporting  
leg coordinate system at time  $t - \Delta t$  shown in Fig. 11) about  
the posture rotational center by the aforesaid variation  
25 in posture rotational error, as the updated current  
estimated supporting leg coordinate system (the estimated  
supporting leg coordinate system at time  $t$  shown in Fig.



11).

The origin and the directions of the coordinate axes of the estimated supporting leg coordinate system are represented by a global coordinate system. It is assumed that initial values of the estimated supporting leg coordinate system (initial position/posture in the global coordinate system) have been set during initialization processing in S010.

The rotational center of the estimated supporting leg coordinate system means a rotational center of slippage rotation of the supporting leg foot 22 in normal walk, which is free of a floating period. In the floating period in a running motion or the like wherein a supporting leg is also apart from a floor during one step, no slippage of the supporting leg foot 22 takes place in a narrow sense. For this reason, a posture rotation (or spin) in the air is preferably expressed by means of a rotation about the rotational center of the estimated supporting leg coordinate system. However, in a broad sense, the "slippage of a supporting leg foot" may be defined as a posture rotation about the rotational center of the estimated supporting leg coordinate system.

Complementarily, the supporting leg coordinate system is set with respect to the ground contact surface of the supporting leg foot 22, and the origin thereof may not be the one vertically projected from the center of the ankle of the supporting leg as described above. In other words,

the supporting leg coordinate system is a local coordinate system set on a virtual floor in the vicinity of the supporting leg foot 22 for describing motions of the robot 1. In effect, the phenomenon of a posture rotation (or spin) of the robot 1 is regarded as a phenomenon in which the virtual floor is posture-rotated (or spun) about a predetermined point in a global coordinate system, as its rotational center, together with the entire robot, while maintaining a state wherein the robot 1 is in motion without relatively posture-rotating (or spinning) on the virtual floor.

In other words, the motion of the robot 1 may be regarded as a perturbational rotation in which the entire robot 1 in motion according to desired gaits or joint detected displacement values in a local coordinate system rotates, together with the local coordinate system, about a predetermined point as its rotational center (posture rotational center) with respect to the global coordinate system.

Hence, the posture rotational center may be defined as the rotational center of an estimated supporting leg coordinate system and also as the rotational center of the perturbational rotation.

Generally, the Z-axis of the current estimated supporting leg coordinate system after the posture rotation in S2206 is not oriented in a vertical direction. Therefore, after the posture rotation, the Z-axis of the

current estimated supporting leg coordinate system may be returned in the vertical direction (a next time gait's estimated supporting leg coordinate system may be rotated about its origin by the inclination angle of the Z-axis relative to the vertical direction). Alternatively, during the posture rotation processing in S2206, the estimated supporting leg coordinate system may be rotated by a component about a vertical axis (spinning component) out of the aforesaid variation in posture rotational error.

The program then proceeds to S2208 in which it is determined whether landing time has been reached, i.e., whether it is a gait switching moment.

If the determination result in S2208 is YES, then the following processing is carried out. First, the program proceeds to S2210 wherein a next time gait's estimated supporting leg coordinate system is determined such that the relative position/posture relationship of the next time gait's estimated supporting leg coordinate system with respect to the current estimated supporting leg coordinate system (the estimated supporting leg coordinate system after the posture rotation in S2206) will be the same as the relative position/posture relationship of the next time gait's supporting leg coordinate system with respect to the supporting leg coordinate system in a desired gait (last time gait), as illustrated in Fig. 12. The next time gait's supporting leg coordinate system in this case means the supporting leg coordinate system of

the gait following the last time gait (i.e., the current time gait), rather than the next time gait's supporting leg coordinate system for the current time gait to be generated. The supporting leg coordinate system of a  
5 desired gait is a coordinate system having its Z-axis oriented in the vertical direction, so that the Z-axis of the next time gait's estimated supporting leg coordinate system that satisfies the aforesaid relative position/posture relationship with respect to the current  
10 estimated supporting leg coordinate system after a posture rotation is not usually oriented in the vertical direction. In the present embodiment, therefore, a next time gait's estimated supporting leg coordinate system is eventually determined by returning, in the vertical direction, the Z-  
15 axis of the next time gait's estimated supporting leg coordinate system that satisfies the above relative position/posture relationship with respect to the current estimated supporting leg coordinate system after a posture rotation (the next time gait's estimated supporting leg  
20 coordinate system is rotated about its origin by an inclination angle of the Z-axis relative to the vertical direction). In S2206, if the Z-axis of the estimated supporting leg coordinates is oriented in the vertical direction, as described above, then the processing for  
25 returning the Z-axis of the next time gait's estimated supporting leg coordinate system in the vertical direction in S2210 will be unnecessary.

Subsequently, the program proceeds to S2212 in which the position/posture (the position of the origin and the directions of the coordinate axes) of the next time gait's estimated supporting leg coordinate system determined in S2210 is substituted into the position/posture of the current estimated supporting leg coordinate system. In other words, the position/posture of the current estimated supporting leg coordinate system is replaced by the position/posture of the next time gait's estimated supporting leg coordinate system.

After S2212 or if the determination result of S2208 is NO, then the program proceeds to S2214 wherein an estimated body position, which is an estimated value of the body position in a global coordinate system, is determined on the basis of the position/posture of the current estimated supporting leg coordinate system. However, the relationship of the estimated body position relative to the current estimated supporting leg coordinate system is set to agree with the relationship of the body position (desired body position) with respect to the supporting leg coordinate system of a desired gait (desired gait determined in a previous control cycle).

Next, the program proceeds to S2216 wherein an inertial-navigation-like estimated body position/posture is determined according to the inertial navigation by the accelerometer and the gyro sensor provided in the inclination sensor 54, and the inertial-navigation-like

body position is corrected so that the difference between a geometrically estimated body position and the inertial-navigation-like estimated body position is converged to zero. More details of this processing will be discussed hereinafter.

The above is the outline of the self position/posture estimation processing in S016 of Fig. 9.

In S2210, desired gaits have been used to determine the next time gait's estimated supporting leg coordinate system. Alternatively, however, a next time gait's estimated supporting leg coordinate system may be determined as described below when walking the robot 1.

First, based on a current (landing instant) joint detected displacement value of the robot 1, actual free leg foot position/posture (the position/posture of the front foot 22 of the robot 1 in the example shown in Fig. 12) at landing in a current estimated supporting leg coordinate system is estimated by kinematics computation. Hereinafter, the estimated actual free leg foot position/posture at landing will be referred to as an estimated free leg foot position/posture at landing.

At this time, however, it is assumed that the robot 1 is in motion according to a joint detected displacement value without the foot 22 of the supporting leg slipping relative to a virtual floor on the current estimated supporting leg coordinate system while the robot 1 maintains a body posture based on a desired gait on the

current estimated supporting leg coordinate system.

Complementarily, it is assumed that the robot 1 maintains the body posture based on the desired gait on the current estimated supporting leg coordinate system  
5 rotated about the posture rotational center by the variation in posture rotational error in order to make the body posture in the assumed figure match with the estimated body posture in a global coordinate system at that moment. Hence, when rotating the current estimated  
10 supporting leg coordinate system only by a vertical axis component (spin component) in the variation in posture rotational error rather than posture-rotating it by the aforesaid difference, it is assumed that the robot 1 is in motion based on a joint detected displacement value  
15 without slippage of the foot 22 of the supporting leg relative to a virtual floor on a current estimated supporting leg coordinate system while the robot 1 maintains the orientation of the body based on a desired gait on the current estimated supporting leg coordinate  
20 system, with the inclination of the body agreeing with an inclination component of the variation in the posture rotational error.

At this time, based on at least one of a floor reaction force detected value by the six-axis force sensor  
25 50 and a floor reaction force of a desired gait, a variation in the deformation mechanism of the foot 22 (the elastic member 106, the ground contact member (sole

elastic member) 71, the bag-shaped member 109, etc. shown in Fig. 3 and Fig. 4) may be determined using a dynamic model (a spring damper model or the like) of the deformation mechanism, and an estimated free leg foot position/posture at landing may be determined, including (considering) the deformation amount. More specifically, as the figure of the robot 1 shown in Fig. 12, a total figure (a total figure of the robot 1 at that moment) is determined when a body posture is defined as a desired body posture in a current estimated supporting leg coordinate system, and a joint displacement is defined as a joint detected displacement value (a  $j$ -th joint detected displacement value  $\theta_j$ ,  $j=1,2 \dots$ ), and a variation amount of the deformation mechanism is defined as an estimated deformation amount estimated on the basis of a floor reaction force detected value. Then, a free leg foot position/posture relative to the supporting leg in the entire figure (the leg 2 at the rear side of the robot 1 shown in Fig. 12) is determined, and the determined position/posture may be used as the estimated free leg foot position/posture at landing. Alternatively, a disturbance observer may be used on the basis of a motor current command or a detected value to estimate a load acting on a decelerator or a link, and deformation of the decelerator or the link may be estimated on the basis of the estimated load so as to determine an estimated free leg foot position/posture at landing, including



(considering) the deformation of the decelerator or the link.

Further alternatively, an estimated free leg foot position/posture at landing may be determined by  
5 kinematics computation on the basis of at least a joint displacement of a desired gait (a desired joint displacement value) and a compliance compensation amount (refer to Japanese Unexamined Patent Application Publication No. 10-277969 previously proposed by the  
10 present applicant).

The above arrangements make it possible to determine estimated free leg foot positions/postures at landing with further improved accuracy.

When walking the robot 1, the processing in S2214 may  
15 use the same technique for determining estimated free leg foot positions/postures at landing to determine the body position relative to a supporting leg coordinate system by kinematics computation on the basis of current joint detected displacement values of individual joints of the  
20 robot 1, and then determine an estimated body position such that the positional relationship of the estimated body position relative to a current estimated supporting leg coordinate system agrees with the above determined positional relationship. In this case, the relationship  
25 among estimated body positions, estimated supporting leg coordinate systems, and joint detected displacement values is as shown in Fig. 12.

Alternatively, a body position relative to a supporting leg coordinate system may be determined by kinematics computation on the basis of at least a joint displacement of a desired gait (a desired joint displacement value) and a compliance compensation amount (refer to Japanese Unexamined Patent Application Publication No. 10-277969 previously proposed by the present applicant), and then the relationship of an estimated body position with respect to an estimated supporting leg coordinate system may be set to agree with the above determined body position.

The above arrangements make it possible to determine estimated body positions with further improved accuracy.

Processing of S2200 and processing of S2216 will now be explained in detail with reference to Fig. 13. In the following explanation, an estimated body position determined in S2214 will be referred to as a geometrically estimated body position.

To explain the processing of S2200 in detail, based on a motion at the geometrically estimated body position determined as described above in a preceding control cycle or earlier, a geometrically estimated body acceleration, which is a second-order differential of the geometrically estimated body position, is calculated. This processing is carried out by a block 301 shown in Fig. 13. It is assumed that the processing for determining the geometrically estimated body position is carried out by a

block 300 shown in Fig. 17. Complementarily, as long as a body representative point and the position of the accelerometer coincide with each other, an estimated body posture is not necessary in calculating a geometrically estimated body acceleration (strictly speaking, the acceleration at the position of the accelerometer in the body 3 that is geometrically estimated).

Subsequently, an accelerometer detected value converted to a global coordinate system value obtained by converting an accelerometer detected value (body detected acceleration value) into a global coordinate system by using an estimated body posture is determined. This processing is carried out by a block 302 shown in Fig. 13. To simplify the explanation, it is assumed here that the position of the accelerometer and the position of the body representative point coincide with each other. If they do not coincide, then an accelerometer detected value and a gyro sensor detected value may be converted into an acceleration and an angular velocity at the body representative point by the kinematics computation or the acceleration and the angular velocity at the body representative point may be converted into an acceleration at a position of the accelerometer and an angular velocity at a position of the gyro sensor.

Then, as illustrated in Fig. 14(a) and Fig. 14(b), the geometrically estimated body acceleration is subtracted from a value obtained by converting an

accelerometer detected value into a global coordinate system value (vector subtraction) so as to determine an estimated gravitational acceleration. The value obtained by converting an accelerometer detected value into a global coordinate system value includes an acceleration component from gravity acting on the accelerometer, while the geometrically estimated body acceleration does not include any acceleration component from gravity. Thus, an estimated gravitational acceleration is determined by subtracting the geometrically estimated body acceleration from the value obtained by converting an accelerometer detected value into a global coordinate system value. This processing is implemented by a block 303 shown in Fig. 13. Fig. 14(a) illustrates a case where the estimated body posture has no error, while Fig. 14(b) illustrates a case where the estimated body posture has an error (hereinafter referred to as an estimated body posture error or an estimated body posture angular error).

Meanwhile, gravitational acceleration assumed to be generated in the vertical direction (Z-axis direction) of a global coordinate system estimated by the robot 1 on the basis of an estimated body posture is referred to as an assumed gravitational acceleration, as shown in Fig. 14(a) and Fig. 14(b).

As previously mentioned, geometrically estimated body acceleration is described using a global coordinate system. The actual robot 1 is in motion, following a desired gait

on the assumption that an estimated body posture correctly estimates an actual body posture. In other words, the robot 1 is in motion, following the desired gait, on the estimated global coordinate system on the assumption that the global coordinate system estimated on the basis of an estimated body position/posture is correct. More strictly speaking, in the self position/posture estimation processing of the robot 1, it is believed that a global coordinate system estimated on the basis of an estimated body position/posture is correct, and a behavior of the actual robot 1 is considered as a result of rotating the robot 1 in motion according to a desired gait on an estimated supporting leg coordinate system, which is a local coordinate system set on a global coordinate system believed to be correct, about a predetermined posture rotational center at a moment determined by a posture rotational center determining means by a variation in a posture rotational error as the difference between a changing velocity of a body posture obtained (detected or estimated) by a posture detecting means at each moment and a body posture changing velocity of a desired gait, the robot 1 rotating together with the estimated supporting leg coordinate system.

Accordingly, if an estimated body posture is correct and a detected value of the accelerometer is free of an error, then the assumed gravitational acceleration and the estimated gravitational acceleration agree with each other,

as shown in Fig. 14(a).

Meanwhile, even if a detected value of the accelerometer includes no error, if an estimated body posture includes an error, then an estimated body posture angular error is produced between the direction of the assumed gravitational acceleration and the direction of the estimated gravitational acceleration, as shown in Fig. 14(b). Thus, expression 42 holds true.

Estimated body posture angular error = Angle formed by assumed gravitational acceleration and estimated gravitational acceleration

... Expression 42

As shown in Fig. 14(a) and Fig. 14(b), it can be understood that, if the difference between an estimated gravitational acceleration and an assumed gravitational acceleration is referred to as an estimated gravitational acceleration error, then the estimated gravitational acceleration error is generated by an error in an estimated body posture provided a detected value of the accelerometer has no error, and the relationship represented by expression 43 exists between a horizontal component of the estimated gravitational acceleration error observed from the global coordinate system estimated by the robot 1 on the basis of an estimated body posture (a component orthogonal to an assumed gravitational acceleration of an estimated gravitational acceleration) and the estimated body posture angular error. Expression

43, however, indicates a relationship between a longitudinal component (X component) of an estimated gravitational acceleration error and a Y-axis component of an estimated body posture angular error. In a case where a relationship between a lateral component (Y component) of an estimated gravitational acceleration error and an X-axis component of an estimated body posture angular error is indicated, the minus sign on the right side may be deleted. Here, the gravitational acceleration is positive.

Horizontal component of estimated gravitational acceleration error =  $-\tan(\text{Estimated body posture angular error}) * \text{Gravitational acceleration}$

... Expression 43

In the present embodiment, an estimated body posture is corrected using an estimated body posture angular error calculated from expression 42 or expression 43 so that an estimated body posture error converges to zero.

Returning to the explanation of the processing of S2200, an estimated body posture angular error is calculated, using expression 42, from the angle formed by the assumed gravitational acceleration and the estimated gravitational acceleration at the current instant (strictly speaking, at the instant of one control cycle before). Alternatively, expression 43 may be used to calculate the estimated body posture angular error from a horizontal component of an estimated gravitational acceleration error at the current instant (strictly

speaking, at the instant of one control cycle before).  
The processing for calculating an estimated body posture  
angular error is carried out by a block 304 shown in Fig.  
13.

5           Subsequently, the estimated body posture angular  
error is converted to a sensor coordinate system (a  
coordinate system having its coordinate axes matched to  
detection axes of the gyro sensor) by a block 305 shown in  
Fig. 13, and then a value obtained by multiplying the  
10       converted value by an integration gain  $K_a$  is integrated to  
determine an estimated gyro sensor drift (an estimated  
value of the drift of the gyro sensor). Furthermore, the  
estimated gyro sensor drift is subtracted from a gyro  
sensor detected value  $\omega_{in}$  (body angular velocity detected  
15       value) by a block 307 so as to determine an angular  
velocity with a corrected drift. In the block 307, a  
drift of a yaw rate is also subtracted, as necessary,  
which will be discussed hereinafter. Then, the angular  
velocity with the corrected drift is converted to a global  
20       coordinate system by a block 350, using an estimated body  
posture, so as to determine a global body angular velocity  
 $\omega_{gl}$ .

Next, a value obtained by multiplying the estimated  
body posture angular error by a gain  $K_b$  by a block 309  
25       shown in Fig. 13 is subtracted from the global body  
angular velocity  $\omega_{gl}$  by a block 308, and then the value  
after the subtraction (the output of the block 308) is



integrated by a block 310 (integrator) to determine a new estimated body posture  $\theta_{estm}$ .

The estimated body posture  $\theta_{estm}$  and angular velocity or the like are represented by quaternion, rotational  
5 matrix or Euler angle or the like.

To ensure effective estimation when estimating a drift of the gyro sensor (estimated gyro sensor drift) by the construction described above, it is a precondition that each factor (each factor's estimated body posture  
10 angular error about a sensor detection axis, i.e., sensor local estimated body posture angular error) of a conversion value (vector) obtained by converting an estimated body posture angular error to a sensor coordinate system is subjected only to an influence of a  
15 drift of a gyro sensor associated with that factor and is not or hardly subjected to influences of drifts of other gyro sensors.

In other words, it is a precondition in that an error of a component about the X(Y)-axis of an estimated body  
20 posture angular error is subjected to an influence of a drift of a gyro sensor for the X(Y)-axis, but not subjected to an influence of a drift of a gyro sensor for the Y(X)-axis.

If the body is suddenly rotated 90 degrees about the  
25 Z-axis of a sensor coordinate system after a component about the X-axis of an estimated body posture angular error is generated due to an influence of a drift of the

gyro sensor for the X-axis, a component about a sensor local X-axis of the estimated body posture angular error is consequently shifted to a component about a sensor local Y-axis of the estimated body posture angular error, because the estimated body posture angular error remains accumulated in a global coordinate system. Hence, for the aforesaid precondition to hold true, it is a prerequisite that an absolute value of a velocity of rotation about the Z-axis of a sensor coordinate system be sufficiently small.

Accordingly, if an absolute value of a gyro sensor detected value for the Z-axis (the vertical axis of the body) is large, then it is preferable to reduce the integration gain  $K_a$  or set it to zero (that is, to make no drift correction of a gyro sensor).

Normally, when the robot 1 moves or works, the vertical axis (trunk axis) of the body 3 is vertical or close to vertical. Hence, the global body angular velocity  $\omega_{glz}$  obtained by converting an angular velocity detected value of a gyro sensor into a global coordinate system takes a value close to an angular velocity detected value of the gyro sensor for the Z-axis.

Thus, as shown in Fig. 15, if an absolute value of the angular velocity  $\omega_{glz}$  about a vertical axis of a global body angular velocity obtained by converting an angular velocity detected value of a gyro sensor into a global coordinate system, then the integration gain  $K_a$  may be set to a small value or zero (i.e., no drift correction

of the gyro sensor may be made).

If an absolute value of a component about the vertical axis of a body rotational velocity of a desired gait of the body 3 or a component about the vertical axis of the body 3 is large, instead of an angular velocity detected value of a gyro sensor, then the integration gain  $K_a$  may be set to a small value or zero (i.e., no drift correction of the gyro sensor may be made).

In summary, if an absolute value of a component about the vertical axis of the body rotational velocity or a component about the vertical axis of the body 3 that is determined on the basis of at least either an angular velocity detected value of a gyro sensor or a desired gait is large, then the integration gain  $K_a$  should be set to a small value or zero (i.e., no drift correction of the gyro sensor should be made).

If an absolute value of a value obtained by subtracting an assumed gravitational acceleration from accelerometer detected value converted into a global coordinate system value or an absolute value of a geometrically estimated body acceleration is large, then an error of the estimated gravitational acceleration tends to be increased due to a detection error of a sensor or insufficient rigidity of the main body of the robot 1. Therefore, the aforementioned gain  $K_a$  should be set to be a small value or zero.

As described above, the actual robot 1 assumes that

the global coordinate system estimated on the basis of an estimated body position/posture is correct and moves to follow a desired gait on the estimated global coordinate system. Hence, in a state wherein a supporting leg is in contact with the ground, even if an estimated body posture includes a large error, an actual body acceleration will not be governed by an actual gravitational acceleration, so that it substantially coincides with a geometrically estimated body acceleration on the estimated global coordinate system. On the other hand, in a floating period, an actual body acceleration is accelerated by being governed by an actual gravitational acceleration, resulting in a considerable shift from a direction of the geometrically estimated body acceleration on the estimated global coordinate system. Hence, the relationship shown in Fig. 14(b) no longer applies. Thus, in the floating period, the accuracy of a geometrically estimated body position tends to be lower than the accuracy of a body position determined by the inertial navigation on the basis of an accelerometer and a gyro sensor with relatively high accuracy. Hence, the gain  $K_a$  should be set to a small value or zero also in the floating period.

If a body position is estimated, taking the deformation of the foot 22 into account, as mentioned above, an estimation error in a deformation amount in the vicinity of a sole tends to increase in a state wherein the foot 22 at the distal end of a leg is in poor contact

with a floor even in a non-floating period, leading to deteriorated accuracy of a geometrically estimated body acceleration. For this reason, the gain  $K_a$  should be set to a small value or zero also when the area of contact  
5 between the foot 22 of a supporting leg and a floor is small.

The state wherein the foot 22 of a leg 2 is in good contact with a floor specifically refers to a state wherein at least one of the following conditions is  
10 satisfied or a plurality of the following conditions are simultaneously satisfied.

a) State wherein the area of contact between the bottom surface of the foot 22 and a floor is large, e.g., the foot 22 is in full contact with the floor (a state of so-called flatfoot).  
15

b) State wherein distributed pressure of a floor reaction force is relatively even.

c) State wherein there are many ground contact locations.

d) State wherein a desired ZMP (or an actual floor reaction force central point) is located at the center or  
20 near the center of the foot 22.

e) State wherein a ground contact pressure or a floor reaction force is high.

f) State wherein a position/posture rate of change of the  
25 foot 22 is small, or strictly speaking, a change in a relative position/posture relationship between the bottom surface of the foot 22 and a floor is small.

The above states may be determined on the basis of, for example, a timing (phase) of a desired gait, a desired ZMP, or a floor reaction force detected value.

Alternatively, the above states may be determined on the basis of detected values of a distributed pressure sensor or a contact sensor, which is not provided in the present embodiment.

To summarize the gain setting method described above, it is desirable to set the gain  $K_a$  to a small value or zero in a state wherein an absolute value of a component about the vertical axis of a body rotational velocity or a component about the axis in the vertical direction of the body 3 that is determined on the basis of at least either an angular velocity detected value of a gyro sensor or a desired gait of is large, a state wherein an absolute value of a value obtained by subtracting an assumed gravitational acceleration from an accelerometer detected value converted into a global coordinate system or an absolute value of a geometrically estimated body acceleration is large, or in a floating period, or in a state wherein a distal end portion (foot) of a leg is not in good contact with a floor.

In other words, the integration gain  $K_a$  should be determined by making comprehensive judgment based on the aforesaid states.

The integration gain  $K_a$  may alternatively be determined on the basis of instantaneous values of the

aforesaid states or a long-term trend.

For the same reason, an integration gain  $K_b$  is preferably set in the same manner as that for the gain  $K_a$ .

5 In S2200 of the present embodiment, in addition to the aforesaid processing, a yaw rate correction (a drift correction in the yaw direction) is also made as follows, depending on situations.

First, whether to correct a yaw rate is determined by a block 311 shown in Fig. 13.

10 To be more specific, at least one or a plurality of the following conditions are prepared as determination conditions, and it is determined to correct a yaw rate if the determination condition or conditions are satisfied.

15 a) An absolute value of a moment (or its differential value) about the vertical axis of a detected floor reaction force is a predetermined value or less.

b) A desired operation is substantially static.

c) Contact between a sole and a floor is considered to be good with no slippage.

20 d) An absolute value of a difference between a posture angular velocity of a desired gait and a gyro detected value (posture angular velocity detected value) is a predetermined value or less.

25 e) An absolute value of a posture angular velocity of a desired gait is a predetermined value or less.

f) An absolute value of a gyro detected value (posture angular velocity detected value) is a predetermined value

or less.

Basically, it will be determined to make a yaw rate correction in a situation wherein no slippage (rotational slippage) takes place or it is difficult for slippage to take place on a ground contact surface between the supporting leg foot 22 and a floor.

The gyro detected values in d) and f) are desirably the values obtained by directly subjecting detected values of the gyro sensor (posture angular velocity detected values represented by raw outputs themselves of the gyro sensor) to yaw rate correction.

Then, when it is determined to perform the yaw rate correction, a body posture when it is assumed that no slippage is taking place between the foot 22 and a floor corresponding to an estimated supporting leg coordinate system (hereinafter referred to as an estimated body posture with no slippage) is calculated by a block 312 shown in Fig. 13 on the basis of at least one of a desired gait, a desired body posture, a desired joint displacement and a joint detected displacement value, and an estimated supporting leg coordinate system stored at a latest landing moment (hereinafter referred to as an estimated supporting leg coordinate system at landing). Then, a difference between the estimated body posture and the estimated body posture with no slippage is determined by a block 313, and the determined difference is converted into a sensor coordinate system by a block 314. The converted



difference is supplied to a block 315 of a feedback control law so as to determine a yaw rate drift. As the feedback control law of the block 315, PID control law, for example, is used. The sum of a value obtained by multiplying a temporal differential value (or a variation in the difference between control cycles) of the above difference (the output of the block 314) by a gain  $K_e$ , a value obtained by multiplying the difference (the output of the block 314) by a gain  $K_f$ , and a value obtained by multiplying an integration value of the difference (the output of the block 314) by a gain  $K_g$  is determined so as to determine the yaw rate drift. Then, the determined yaw rate drift is subtracted from the aforesaid angular velocity sensor detected value  $\omega_{in}$  by the block 307. If it is determined not to perform the yaw rate correction, then input of the feedback control law to the block 315 is shut off (a switching 316 in Fig. 13 is opened), an immediately preceding yaw rate drift value is retained, and the value is subtracted from the angular velocity sensor detected value  $\omega_{in}$ . To determine an estimated body posture with no slippage, as in the case where a free leg foot position/posture at landing is estimated in S2210 of Fig. 10, the deformation amount of the deformation mechanism of the foot 22 (the elastic member 106 and the ground contact member (sole elastic member) 71, the bag-shaped member 109, etc. shown in Fig. 3 and Fig. 4) is determined using a dynamic model (spring damper model or

the like) of the deformation mechanism on the basis of a floor reaction force detected value and/or a floor reaction force of a desired gait. Then, the estimated body posture with no slippage may be determined, including (considering) the above deformation amount. Alternatively, a disturbance observer may be used on the basis of a motor current command or a detected value to estimate a load acting on a decelerator or a link, and deformation of the decelerator or the link may be estimated on the basis of the estimated load so as to determine an estimated body posture with no slippage, including (considering) the deformation of the decelerator or the link.

Further alternatively, an estimated body posture with no slippage may be determined by kinematics computation on the basis of at least a joint displacement of a desired gait and a compliance compensation amount (refer to Japanese Unexamined Patent Application Publication No. 10-277969 previously proposed by the present applicant).

The above arrangements make it possible to determine estimated slippage-free body postures with further improved accuracy.

Referring now to Fig. 13, processing of S2216 of Fig. 10 will be explained in detail. In the processing of S2216, a difference between a previous value of an inertial-navigation-like estimated body position Xinertestm and the aforesaid geometrically estimated body position is determined by a block 317, and a sum of a

value obtained by multiplying a temporal differential value of the above difference (or a variation in the difference between control cycles) by a gain  $K_c$  and a value obtained by multiplying the difference by a gain  $K_d$  is determined by a block 318, as shown in Fig. 13. In other words, the sum is determined from the difference by PD control law as the feedback control law. Furthermore, a difference between the accelerometer detected value converted into a global coordinate system value, which is an output of the block 302, and an assumed gravitational acceleration  $G$  is determined by a block 319. Then, a value obtained by subtracting the above sum (the output of the block 318) from the difference (the output of the block 319) by a block 360 is subjected to second-order integration by a block 320 so as to determine a new inertial-navigation-like estimated body position  $X_{inertestm}$ .

The gains  $K_c$  and  $K_d$  should be set to a small value or zero in a situation where a large error in a geometrically estimated body position tends to be produced. If the area of contact between the bottom surface of the foot 22 of a supporting leg and a floor is small, then a large error results in a geometrically estimated body position. If, therefore, the area of contact between the bottom surface of the foot 22 of a supporting leg and a floor is small, then the gains  $K_c$  and  $K_d$  should be set to a small value or zero. Especially when the foot 22 is fully in contact

with a floor (the "flat-footed"), the gains  $K_c$  and  $K_d$  should be set to larger values.

Thus, in a running mode, for example, correction gains  $K_a$ ,  $K_b$ ,  $K_c$  and  $K_d$  may be set to large values while the full sole surface is in contact with the ground and set to zero or substantially zero in the floating period, as indicated by the graph of correction gain  $K$  shown in Fig. 8(c). Although the graph of the correction gain  $K$  in Fig. 8(c) indicates a trend of change in magnitude of  $K_a$ ,  $K_b$ ,  $K_c$  and  $K_d$ , the graph does not show precise values. In Fig. 8(c), the correction gains have been standardized such that the maximum value of the correction gain  $K$  is 1. Hence,  $K$  may be considered to mean a restrictor (damper) of the correction gains  $K_a$ ,  $K_b$ ,  $K_c$  and  $K_d$ .

In the present embodiment, an estimated body posture has been corrected on the basis of an estimated body posture error calculated according to expression 42 or expression 43 shown above. Alternatively, however, an estimated body posture may be directly corrected on the basis of a horizontal component of an estimated gravitational acceleration error without using expression 42 and expression 43. In other words, expression 44 given below may be used in place of expression 43.

Horizontal component of estimated gravitational  
acceleration error = -Estimated body posture error angle \*  
Gravitational acceleration

... Expression 44

To add more explanation of the setting of the gain  $K_a$ , in the floating period, whatever value an estimated body posture error takes, the entire robot 1 behaves as if it were in a weightless state as observed from a coordinate system in a parabolic motion together with the robot 1, so that outputs of the accelerometer are not influenced by errors in estimated body postures. For this reason, an estimated gravitational acceleration and an assumed gravitational acceleration always substantially agree with each other if a condition (hereinafter referred to as "condition A") in which detection accuracy of the accelerometer is high, the actual robot 1 exhibits high performance of following a desired gait, rigidity of the robot 1 is high, and parameters of a robot dynamic model used for generating desired gaits substantially agree with the actual robot 1 is satisfied. Strictly speaking, an estimated gravitational acceleration and an assumed gravitational acceleration deviate from true values by the same amount according to an estimated body posture error. As a result, estimated gravitational accelerations and assumed gravitational accelerations always substantially agree with each other. Essentially, therefore, it is impossible to estimate any gravitational directions in a floating period. However, since estimated gravitational accelerations and assumed gravitational accelerations always substantially agree with each other, the estimated body posture error at that moment is substantially zero.

Hence, even if the gain  $K_a$  is not set to a small value, a correction amount determined by multiplying an estimated body posture error by the gain  $K_a$  will be also substantially zero, being less likely to exert considerably adverse influences on estimated body postures.

If the aforesaid condition A is satisfied, the accuracy of a low-frequency component (DC component) of an estimated body posture rather increases in some cases by holding the gain  $K_a$  constant. This is because, as described above, according to a construction adapted to make a correction so as to reduce a value obtained by integrating a value multiplied by the gain  $K_a$  to zero, the gain  $K_a$  held at a constant value theoretically works to set a long-time mean value of a horizontal component of an estimated gravitational acceleration error to zero, and if an estimated body posture error is zero, then the long-time mean value of the horizontal component of an estimated gravitational acceleration error is theoretically zero. Normally, however, it is difficult to satisfy the condition A, so that the gain  $K_a$  is desirably set as shown in Fig. 8(c).

As an alternative, the value of the correction gain  $K_a$ ,  $K_b$ ,  $K_c$  or  $K_d$  may be determined using a stationary Kalman filter technique or a nonstationary Kalman filter technique. However, in the robot 1 according to the present embodiment, properties of system noises (disturbance) and observation noises do not fully satisfy

prerequisites of the Kalman filters especially during travel, so that satisfactory effect is not necessarily produced.

5 The following is a complementary explanation of the posture rotational center determined in the present embodiment. During a period in which one of the legs 2 is in contact with the ground and a sufficiently large floor reaction force is being generated, a posture rotational center is considered to lie in a so-called supporting  
10 polygon (a smallest convex polygon including a ground contact surface, a range allowing ZMP to be therein, or a range allowing a total floor reaction force central point to be therein).

The following described a reason for the above. If a  
15 posture rotational center lies outside a supporting polygon, then every point on the bottom surface of the foot 22 will be relatively moving with respect to a floor, so that kinetic friction acts on every point of contact between the bottom surface of the foot 22 and the floor.  
20 The kinetic friction remains at a constant value even when the robot 1 moves the leg 2 to control a floor reaction force, and therefore cannot be controlled to an arbitrary value. This is identical to a state in which the robot 1 can hardly walk on slippery ice. Therefore, if the robot  
25 1 is stably moving while controlling floor reaction forces, it is considered that static friction is acting in a certain region between the bottom surface of the foot 22

and the floor, preventing slippage. In other words, a posture rotational center is considered to lie in a supporting polygon. Complementarily, if the foot 22 of the robot 1 is completely rigid, then slippage would take place at every contact point other than the posture rotational central point. However, the bottom surface of the actual foot 22 is formed of an elastic member, such as rubber, so that it is considered that slippage does not occur even in the vicinity of the posture rotational center.

In the floating period, the robot is considered to perform perturbational motion about the center of gravity.

In a period other than the above, namely, in a period in which one of the legs 2 is in contact with the ground although a sufficient floor reaction force has not yet been produced, the posture rotational center is considered to exist between a supporting polygon and the position of a total center of gravity (or a position of a representative point of the body) when motional continuity is taken into account.

Based on the above consideration, more generally, the posture rotational center to be determined in S2204 of Fig. 10 described above is preferably one of the following.

At current time  $t$ ;

- a) Desired ZMP,
- b) Actual ZMP (specifically, an actual floor reaction force central point or a pressure central point of floor



reaction force),

c) Predetermined point, e.g., origin, of a supporting leg coordinate system,

d) Total center of gravity,

5 e) Representative point of the body

f) Internally dividing point of a plurality of one of the above

10 In a period wherein one leg is in contact with the ground and a sufficiently large floor reaction force has been generated, the posture rotational center should be set in a supporting polygon. To be more specific, the posture rotational center may be set to a) and b) shown above. Alternatively, a predetermined point mentioned in c) above may be set such that the posture rotational  
15 center is included in a supporting polygon. For instance, the posture rotational center may be set at the origin (normally the bottom of an ankle joint) of a supporting leg coordinate system.

20 In a floating period, the posture rotational center should be set according to d) above. The position of a total center of gravity is present near the position of a representative point of the body, so that it may be set according to e).

25 In a period other than those described above, namely, during a period wherein one leg 2 is in contact with the ground, but a sufficiently floor reaction force has not yet been produced, setting should be made as per f).

Furthermore, considering the continuity of motion over all periods, the posture rotational central point is preferably set to exhibit a continuous change.

At any rate, at almost every moment, it is desirable  
5 to set posture rotational central points on a surface of  
or inside a smallest convexity that includes the entire  
robot 1.

In the embodiment explained above, the accelerometer  
and/or the gyro sensor are installed on the body 3;  
10 however, they may alternatively be mounted on  
(incorporated in) other part, such as the head 4. If  
there is a neck joint between the head 4 and the body 3,  
detected values of the accelerometer and/or the gyro  
sensor are converted into the accelerations and angular  
15 accelerations of a representative point of the body by  
kinematics computation on the basis of displacement  
commands (desired displacements) or detected displacement  
values of the neck joint, and the rest may be accomplished  
by estimating self positions, as in the above embodiments.

20 When joint displacements are used to determine  
estimated supporting leg coordinate systems and  
geometrically estimated body positions, the joint  
displacements were the joint displacements of desired  
gaits or joint detected displacement values.  
25 Alternatively, the joint displacements may be weighted  
averages. The weight for this purpose may be frequency  
characteristics.

Estimated positions/postures, such as estimated supporting leg coordinate systems and estimated body positions/postures, may be expressed in terms of perturbations from desired positions/postures instead of expressing them by using global coordinate systems as references, as in the aforesaid embodiment.

In the above embodiment, as shown in Fig. 13, an estimated body posture angular error in a global coordinate system has been determined on the basis of an estimated gravitational acceleration in a global coordinate system, and a value obtained by multiplying the estimated body posture angular error in the global coordinate system by the gain  $K_b$  is additionally supplied to the integrator (the block 310 shown in Fig. 13) that integrates the global body angular velocity  $\omega_{gl}$  so as to correct the estimated body posture. In other words, estimated body postures have been corrected in global coordinate systems; however, they may alternatively be corrected on local coordinate systems (coordinate systems fixed to the body 3) of the gyro sensor. More specifically, in Fig. 13, the block 309 of the gain  $K_b$  and an adder (the block 308) that subtracts an output of the block 309 from the global body angular velocity  $\omega_{gl}$  may be deleted, and the integrator  $K_a/S$  (the block 306) may be replaced by  $K_a/S+K_b$ , namely, a block of PI control law.

In principle,  $K_b$  would not lead to poor convergence of an inclination drift in turning (including the turning

on the spot) with a high yaw rate even if a correction is made using a local coordinate system, as described above.

To correct an estimated body posture, an estimated gravitational acceleration may be determined by subtracting a body acceleration of a desired gait from an accelerometer detected value converted into a global coordinate system value in place of determining the estimated gravitational acceleration by subtracting a geometrically estimated body acceleration from an accelerometer detected value converted into a global coordinate system value.

In an actual operation, when a robot is about to move according to a desired gait, a posture rotation about a posture rotational center is generated, so that the posture rotation causes a body acceleration to deviate from the desired gait. However, a posture inclination in the posture rotation remains zero on the average even if longitudinal or lateral shakes occur. Furthermore, the direction of spin in posture rotation is reversed for each step, so that the spin is close to zero on the average. Therefore, except for those forces, such as a centrifugal force, that act substantially in the same direction regardless of the rotational direction of posture rotation, positive influences and negative influences on the body acceleration caused by posture rotations cancel each other. As a result, the influences will be substantially zero in the long term. The "long term" here refers to a period of

time not less than the stabilization time of correcting an estimated body posture.

Thus, there will not be marked deterioration of correcting effect even if body accelerations of desired gaits are used instead of geometrically estimated body accelerations to correct estimated body postures.

As explained above, in the aforesaid embodiment, estimated body positions (inertial-navigation-like estimated body position) and estimated body postures are determined by inertial navigation, and the inertial-navigation-like estimated body positions and estimated body postures are corrected using geometrically estimated body positions. This makes it possible to accurately estimate self positions/postures, and landing positions and directions (positions and directions of estimated supporting leg coordinate systems) of the robot 1.

#### Industrial Applicability

As described above, the present invention is useful, providing a technology that makes it possible to accurately estimate a posture of a predetermined part, such as a body, of a leg type moving robot, such as a bipedal moving robot.